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TITLE: Test Case RCM-3 Using CPS

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TEST CASE RCM-3 USING CPS

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1. GENERAL PRESENTATION

1.1. Introduction

The test case RCM-3 consists of modeling the MASCOTTE combustor at a pressure chamber of 60 bar, which is higher than the critical pressure of liquid oxygen (50.4 bar). This range of pressure is thought to be representative of the chamber pressure encountered in real engine.

The CPS code (version 1.3) was used to model this test case. Various models have been compared between them and to the experimental results available.

1.2. Geometry of MASCOTTE

The MASCOTTE test combustor has a square section of 50 x 50 mm. The chamber length is fixed at 400 mm.

The injector head consists of a single coaxial injector element (Figure 1).

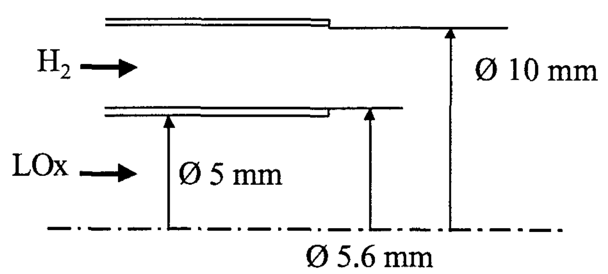


Figure 1 : injector geometry

1.3. Operating condition

The operating point is the A-60 case. It is defined in the following table:

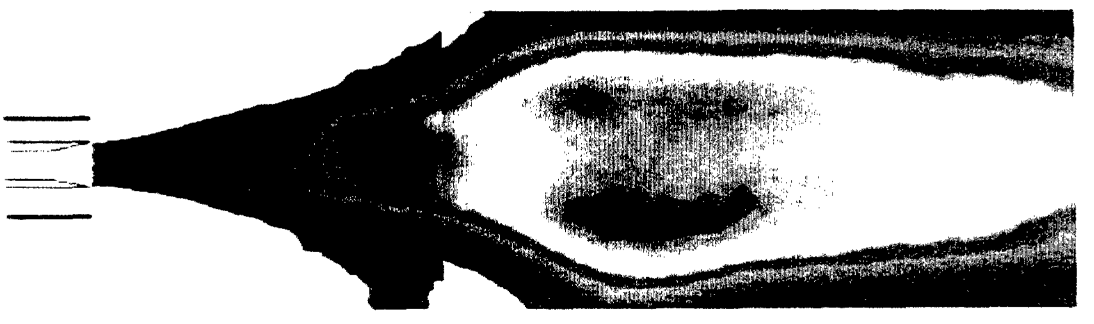
Pressure	O / F	$\dot{m}$ (LOx)	$\dot{m}$ (H_2)
60 bar	1.4	100 g/s	70 g/s

In this case [1], liquid oxygen is injected at 85 K, while gaseous hydrogen is injected at approximately 287 K. The physical properties of the propellants are summarized in the following table:

Conditions	H_2	O_2
Pressure	6 Mpa	6 MPa
Mass flow	70 g/s	100 g/s
Temperature	287 K	85 K
Density	5.51 kg/m^3	1177.8 kg/m^3
Cp	15110 J/kg/K	1660.9 J/kg/K
Velocity	236 m/s	4.35 m/s
Surface tension	8.67 10^{-4} kg/m/s	2.34 10^{-4} kg/m/s

1.4. Experimental results

Available data for this test case is OH emission. Abel transform permit to have an axisymetrical view of the flame (Figure 2)



Average OH* emission image for operating point A-60

Abel transform emission image for operating point A-60

Figure 2 : Experimental result for operating point A-60

1.5. Physical phenomena

The phenomena involve in such case are summarize in the Figure 3.

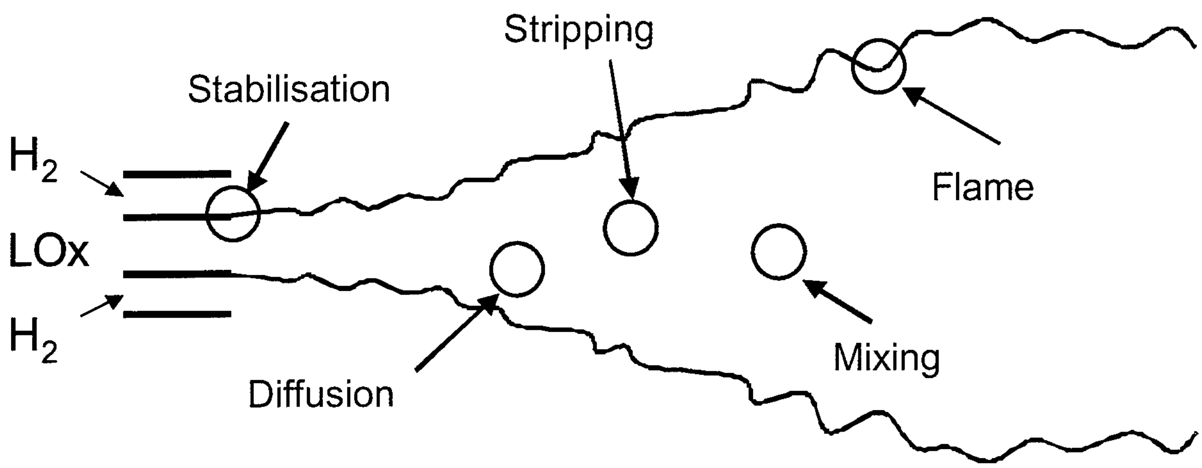


Figure 3 : Physical phenomena in supercritical condition.

1.6. Oxygen thermodynamics properties

Various thermodynamics properties of oxygen at 60 bar are plot on Figure 4. We observe important variation between injection temperature (85 K) and boiling temperature (119 K).

Critical temperature and pressure are respectively 154 K and 5.04 MPa.

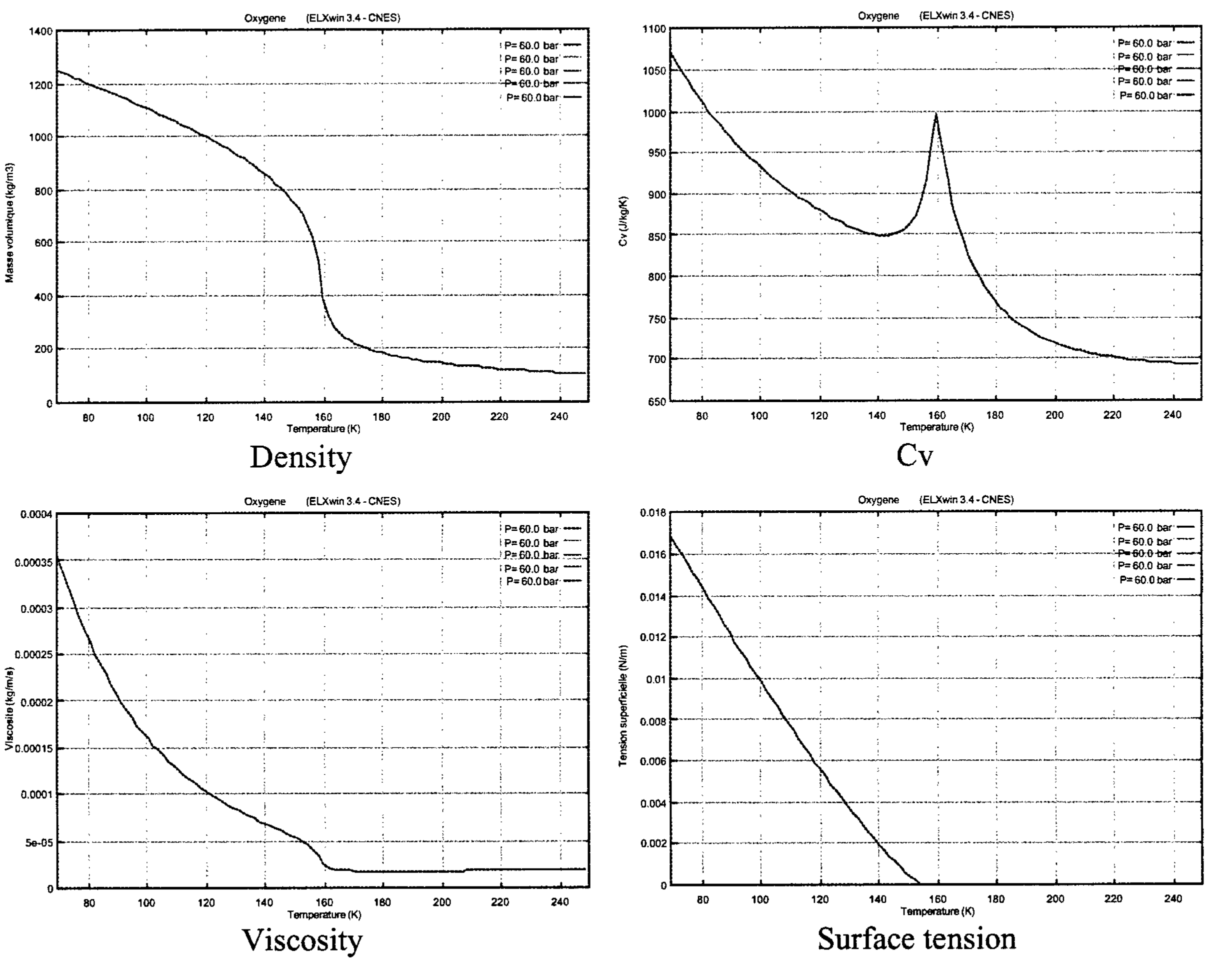


Figure 4 : Evolution of oxygen thermodynamics properties between 70 et 250 K at 60 bars.

2. MODELING

2.1. Mesh

The mesh is composed of 37 x 58 cells as represented in Figure 5.

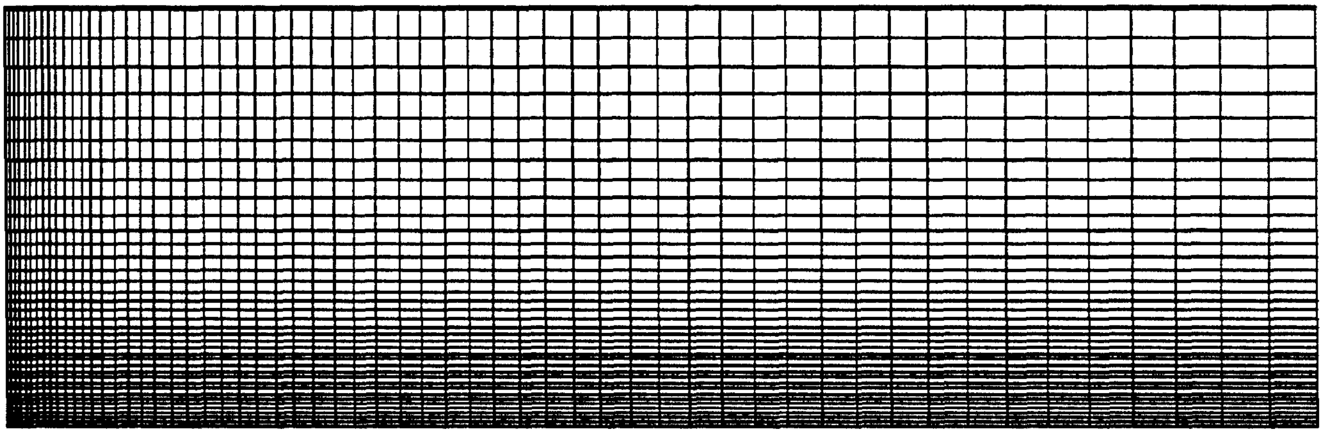


Figure 5 : Mesh (representation dilated by 5 on vertical direction)

2.2. Conditions

Calculation have been made with constant parameter and model as:
- Lagrangian approach
- Explicit scheme
- Droplet fragmentation model (TAB)
- Droplet vaporization model
- Without droplet collision
- Initial droplet diameter (50 μm)

Other parameter and model have been compared:

2.2.1. Injection condition

Injection of liquid in critical condition is not well known. It's clear that injection of one size droplet is not representative. So we have used different injection condition for oxygen:
- Gas
- Liquid
- Mixture with Gas / Liquid ratio variable

2.2.2. Turbulence model

Two turbulence model have been used:
- q-ω Coakley
- k-ε Jones-Launder

q-ω Coakley	k-ε Jones-Launder
$\mu^t = C_\mu f_d \dfrac{\rho k}{\omega}$	$\mu^t = C_\mu f_d \dfrac{\rho k}{\omega}$
$s_1 = q = k^{1/2}$	$s_1 = k = q^2$
$s_2 = \omega = \dfrac{\varepsilon}{k}$	$s_2 = \varepsilon = \omega k$
$H_q = \dfrac{1}{2}\left[C_\mu f_d \dfrac{S}{\omega^2} - \dfrac{2}{3}\dfrac{D}{\omega} - 1\right]\rho\omega q$	$H_k = \left[C_\mu f_d \dfrac{S}{\omega^2} - \dfrac{2}{3}\dfrac{D}{\omega} - 1\right]\rho\omega k$
$H_\omega = \left[C_1\left(C_\mu \dfrac{S}{\omega^2} - \dfrac{2}{3}\dfrac{D}{\omega}\right) - C_2\right]\rho\omega^2$	$H_\varepsilon = \left[C_1\left(C_\mu f_d \dfrac{S}{\omega^2} - \dfrac{2}{3}\dfrac{D}{\omega}\right) - C_2 f_e\right]\rho\omega\varepsilon$

2.2.3. Combustion model

Two combustion model have been used:

- Coherent flame model (CFM)
- Eddy Break Up model (EBU)

CFM	EBU
$S^c_{\rho S_f} = \alpha\rho\varepsilon_S S_f \dfrac{\dot{Q}_h}{\dot{Q}_{h0}} - \beta\rho S_f^2 \dfrac{\dot{Q}_{k\lim}}{Y_{k\lim}}$	$\dot{\omega} = \dfrac{\rho}{Stoemas_{k\lim}} C_{EBU} Y_{k\lim}\left(Y^0_{k\lim} - Y_{k\lim}\right)$
with $\varepsilon_S = C_S \dfrac{\varepsilon}{k}$	$S^c_{\rho Yk} = Stoemas(k)\dfrac{\Delta t\dot{\omega}}{\rho}$

2.2.4. Oxygen thermodynamics properties

The oxygen thermodynamics properties have take constant in our calculus. To take into account the droplet temperature increase we have take different thermodynamics properties for the oxygen.

	Injection (85K)	Boiling (119K)
Density (kg/m^3)	1177.8	1004.4
Viscosity (kg/m/s)	$2.34\ 10^{-4}$	$1.05\ 10^{-4}$
Surface tension (N/m)	$1.32\ 10^{-2}$	$5.82\ 10^{-3}$
Cv (J/kg/K)	987.5	880.6

2.3. Different case

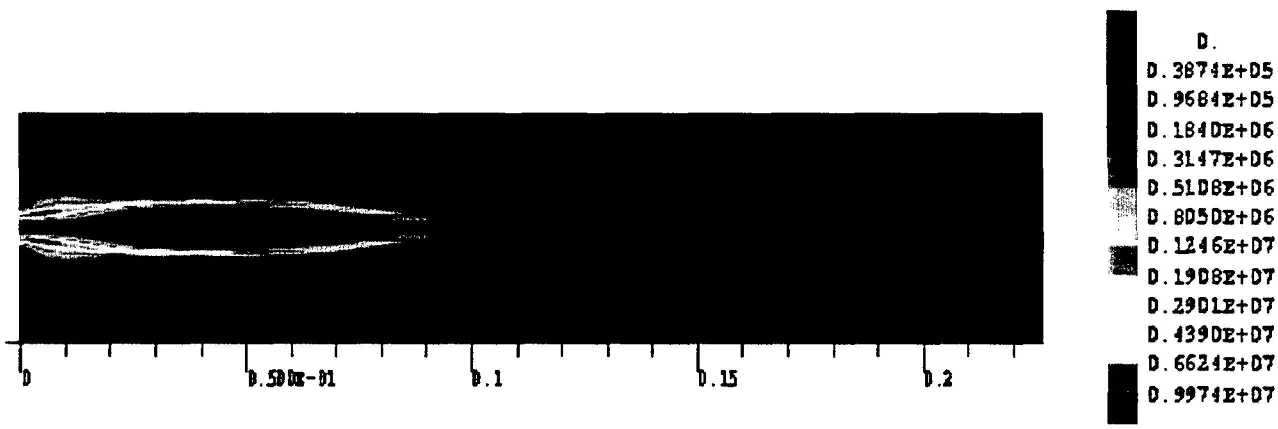
The different case test are summarize in the following table (the variable parameter are in italic):

Injection	Combustion model	Turbulence model	Oxygen thermodynamics properties
Gas *Liquid*	EBU	q - ω	Injection (85 K)
Liquid *Mixture*	CFM	q - ω	Injection
Mixture ratio	CFM	k - ε	Boiling (119 K)
Liquid	*CFM* *EBU* *EBU/Arrhénius*	q - ω	Injection
Mixture	*EBU* *CFM*	k - ε	Injection
Mixture	CFM	*q - ω* *k - ε*	Injection
Liquid	CFM	q - ω	*Injection* *Boiling* *Cv / ρ / enthalpy / μ*
Mixture	CFM	k - ε	*Injection* *Boiling* *Surface tension*

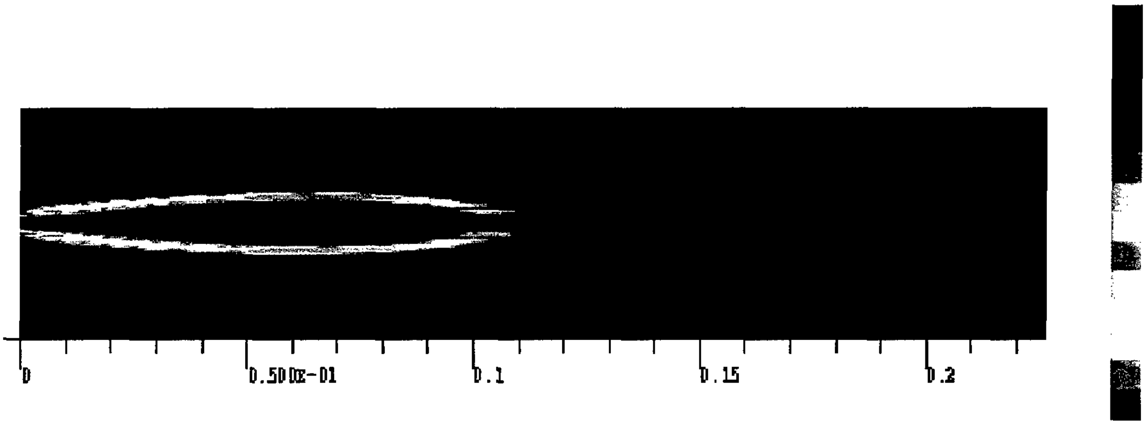
3. RESULTS

3.1. Injection influence

We observe an important variation of the flame length with the ratio gas / liquid injected (Figure 6 and Figure 7). The flame length increases with the liquid fraction (Figure 6). This phenomenon is due to the time increased necessary to vaporize all the droplets. We also observe a modification of the reactive zone on the near field of the injector due to the presence of gaseous oxygen.



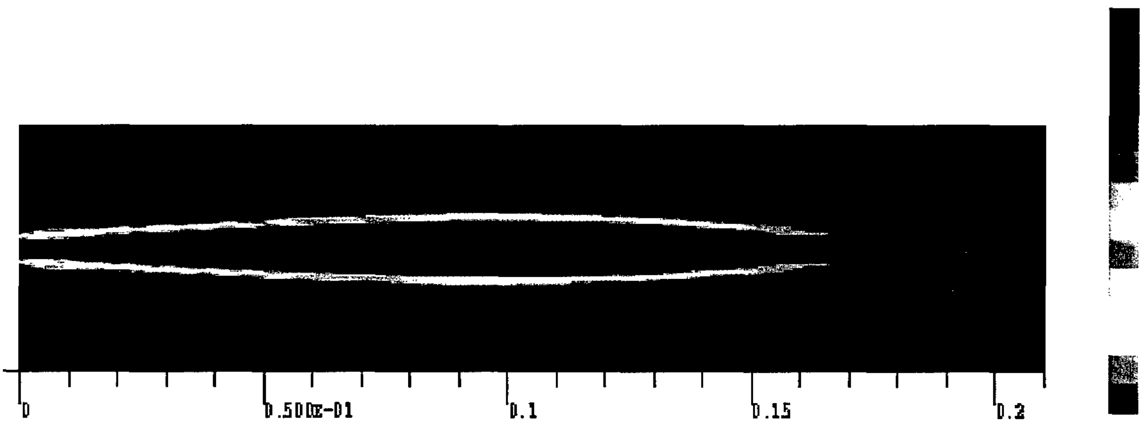
Injection Gas – Liquid (1:1)



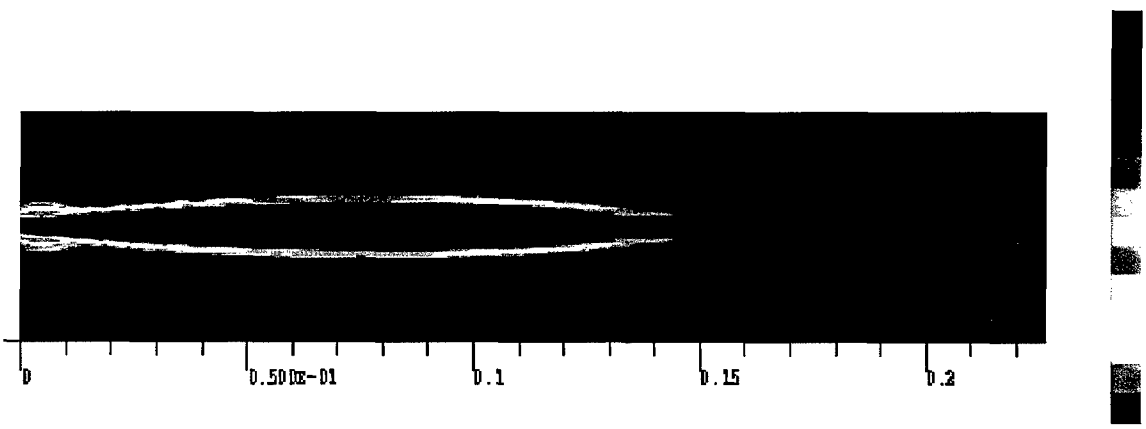
Injection Liquid

Figure 6 : Reactive rate (mol/kg/s) : CFM, q - ω; oxygen (injection)

If we decrease drastically the liquid fraction, the flame length increases (Figure 7). This is due to the increase of the oxygen injection speed to obtain the correct amount of oxygen injected.



Injection Gas – Liquid (4:1)



Injection Gas – Liquid (1:1)

Figure 7 : Reactive rate (mol/kg/s) : CFM, k - ε; oxygen (injection)

We observe on Figure 8 that liquid oxygen volume fraction can be find greater that one (red part on the figure). This is physically incorrect and due to the fact that CPS neglect the volume of the droplet. To minimize this effect, in most case, we have take a gas-liquid mixture for oxygen injection.

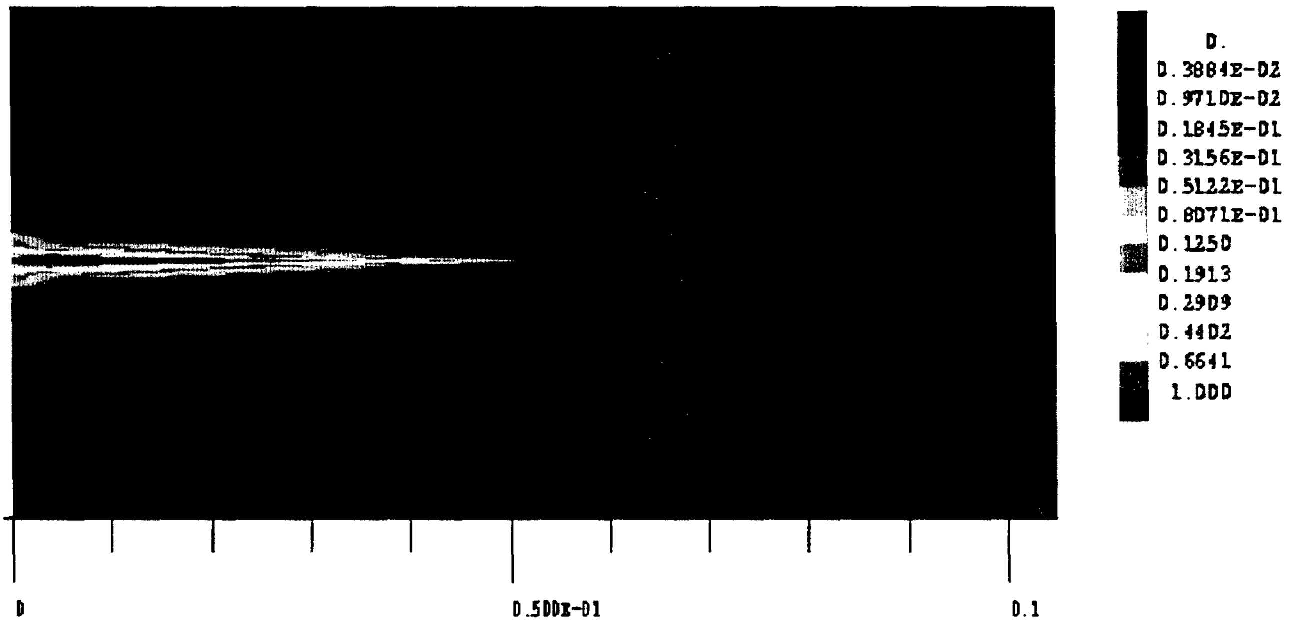
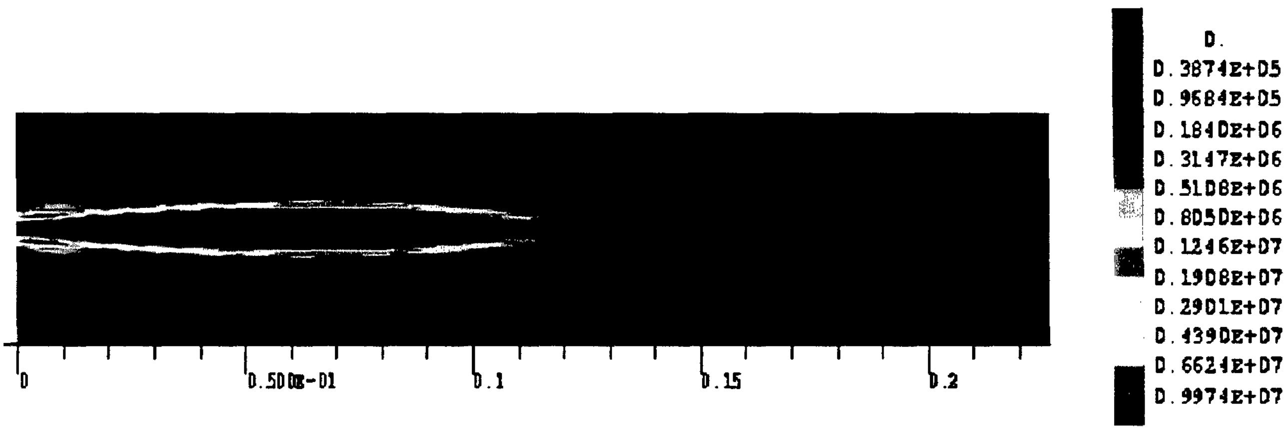
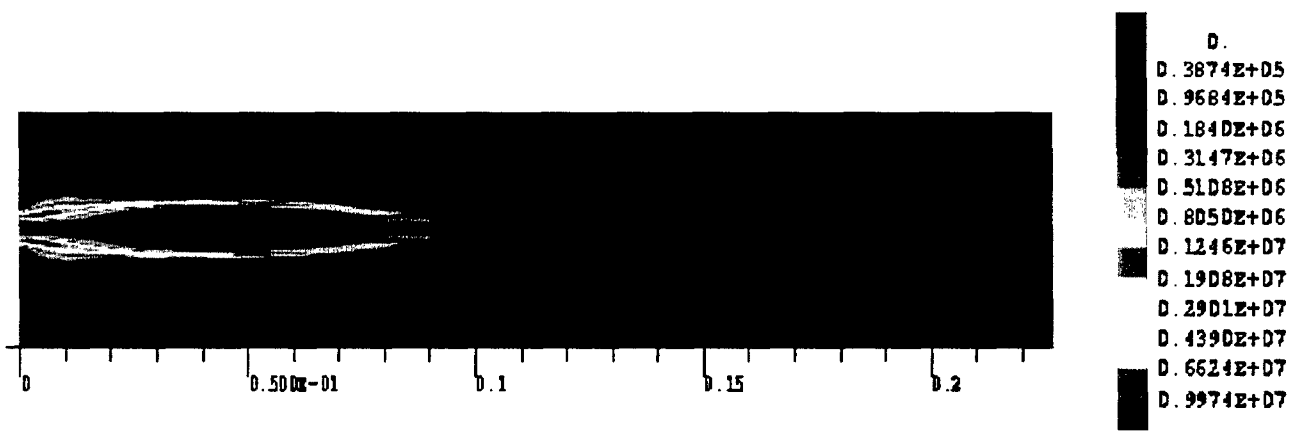


Figure 8 : Liquid oxygen volume fraction

3.2. Turbulence model influence



k - ε



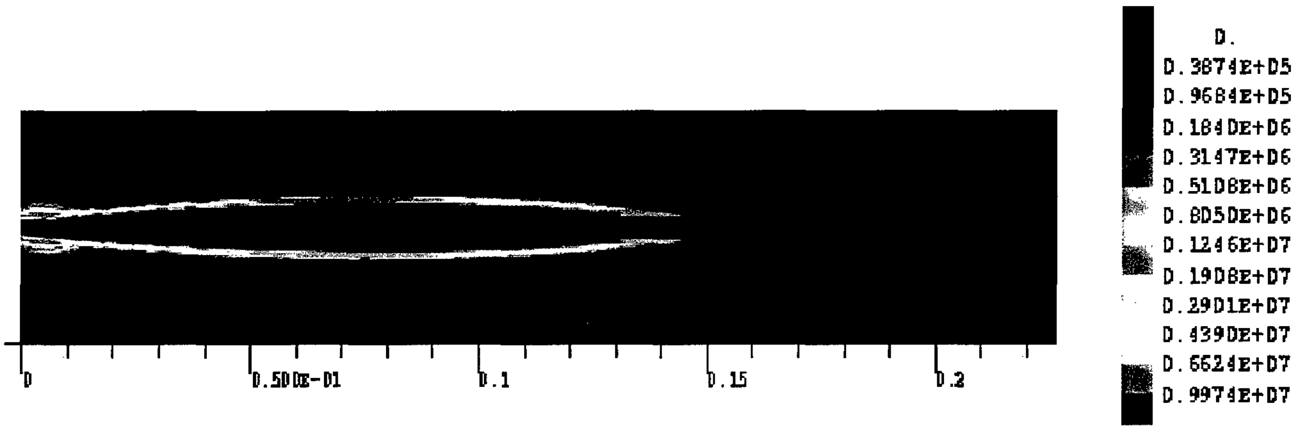
q - ω

Figure 9 : Reactive rate (mol/kg/s) : CFM, Gas – Liquid (1:1), oxygen (injection)

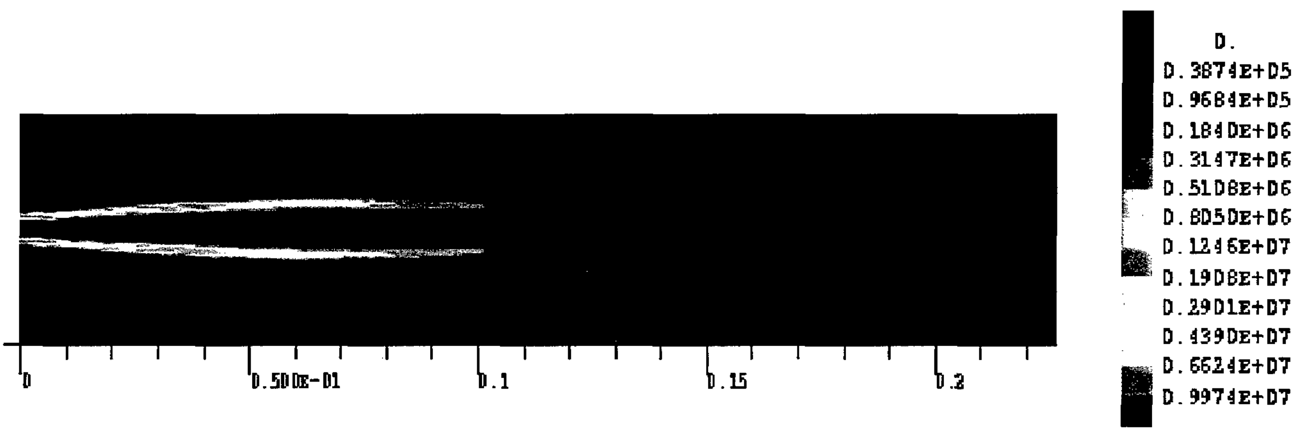
3.3. Combustion model influence

We observe important variation of the flame structure between the two models (Figure 10 and Figure 11). With Gas+Liquid injection: EBU model gives a better flame structure in the injector near field. But the CFM gives better results for:

- Temperature value (Figure 12)
- Flame structure

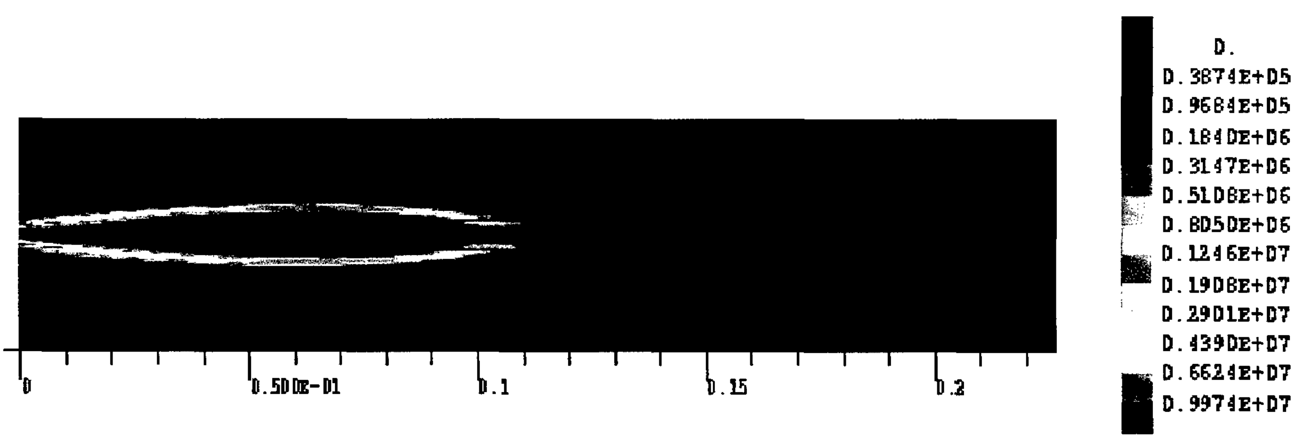


CFM

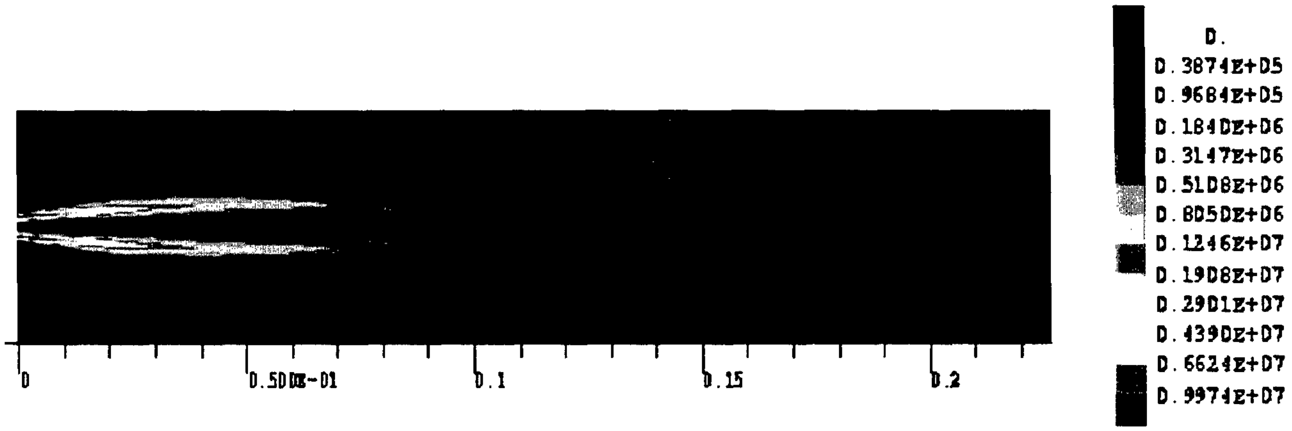


EBU

Figure 10 : Reactive rate (mol/kg/s) : Gas – Liquid (~1:1), k - ε, oxygen (injection)

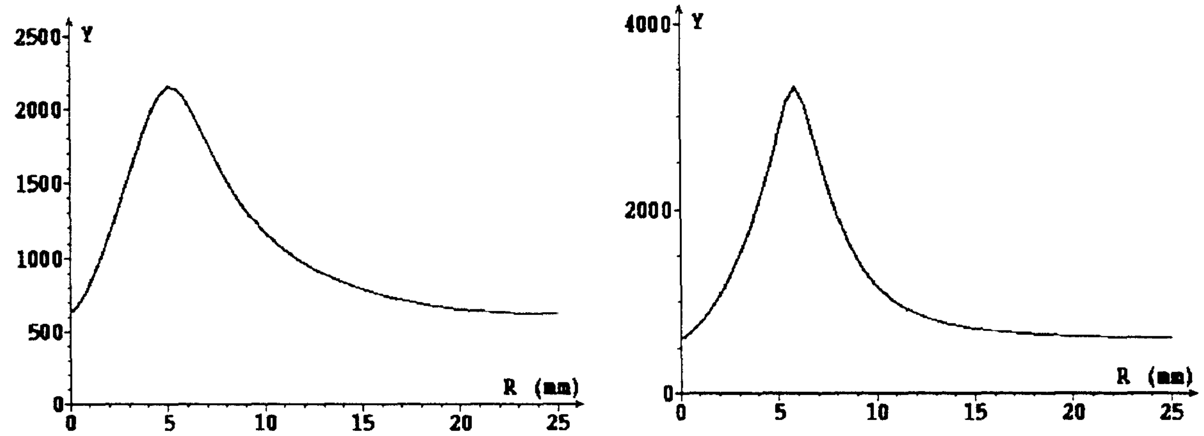


CFM



EBU

Figure 11 : Reactive rate (mol/kg/s) : Liquid, q - ω, oxygen (injection)

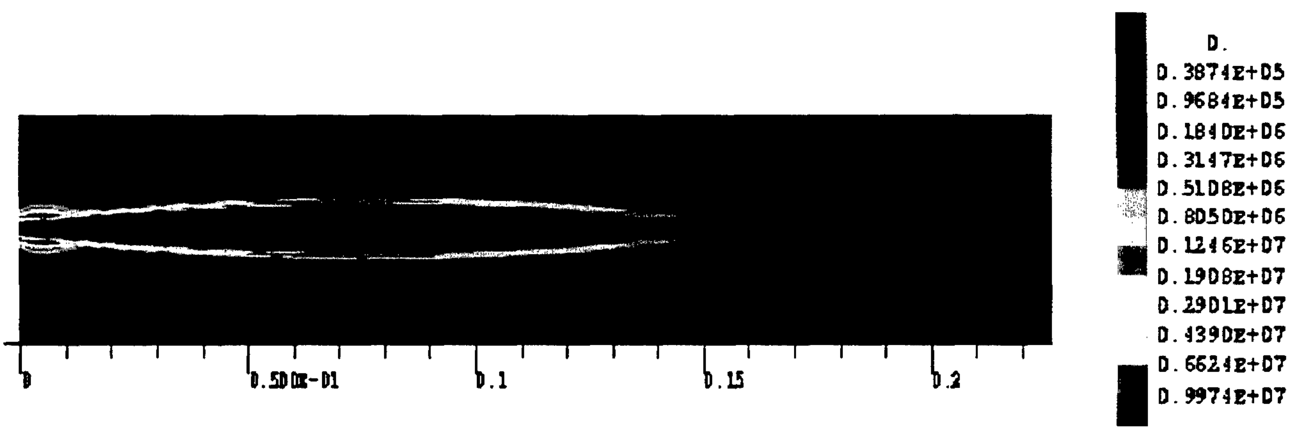


EBU CFM

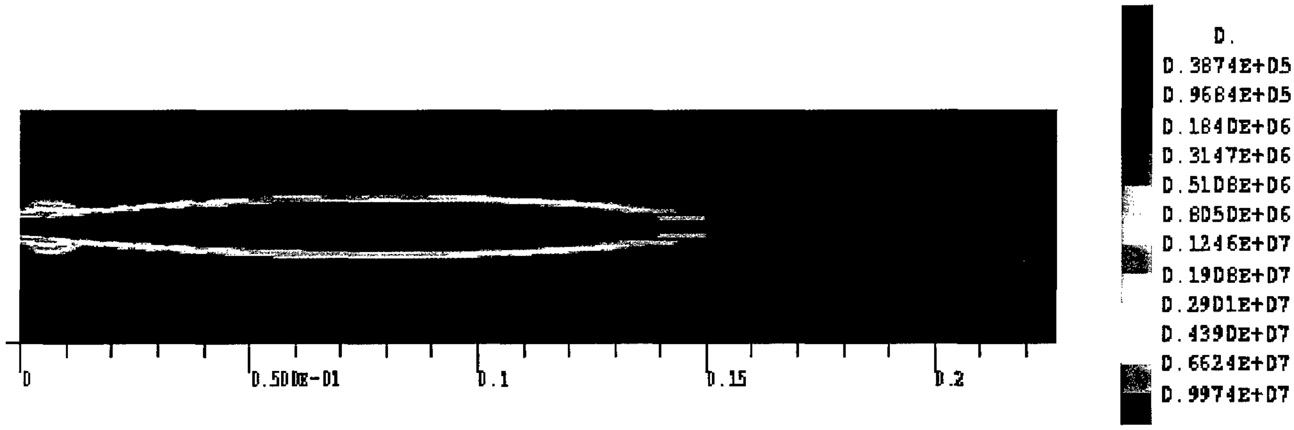
Figure 12 : Temperature radius profile (x = 50 mm) : Liquid, q - ω, oxygen (injection)

3.4. Oxygen thermodynamics properties influence

When we change oxygen thermodynamics properties, we don't observe difference in the results except in the near field of the injector. This is due to the modification of the surface tension and the increase of breakup with decreasing σ ($\sigma = 1.32\ 10^{-2}$ N/m at 85K et $5.82\ 10^{-3}$ N/m at 119K).



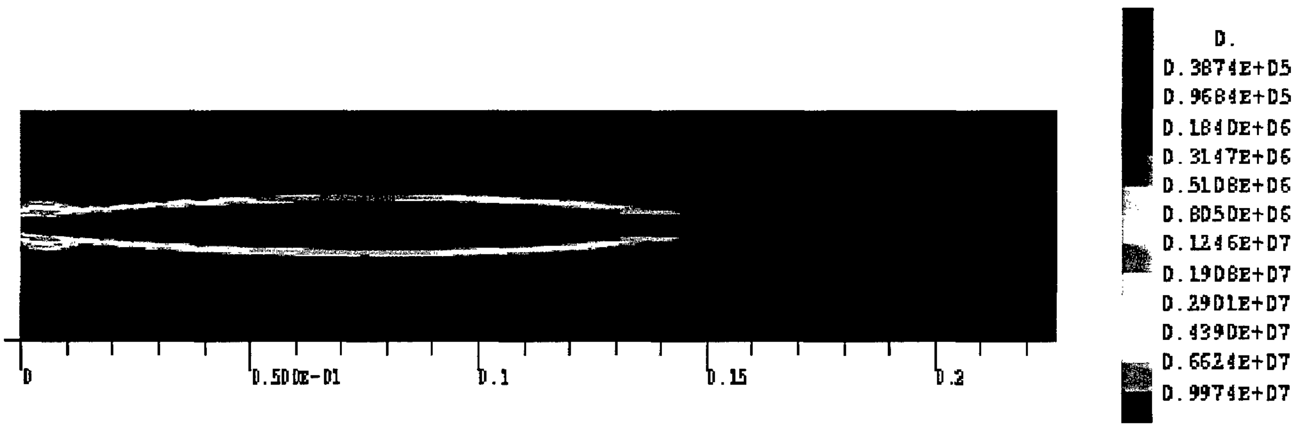
Thermodynamics properties at 85 K (Injection)



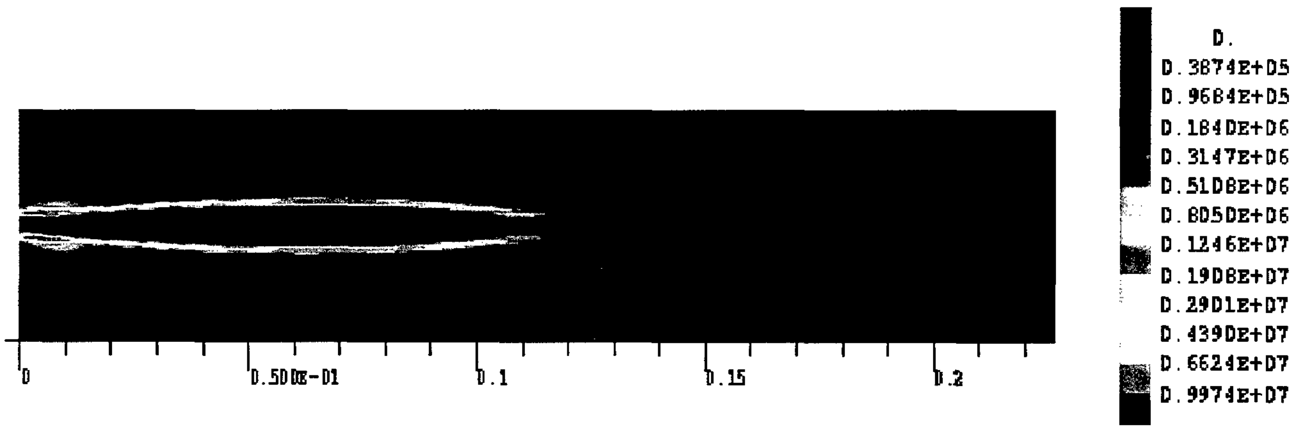
Thermodynamics properties at 119 K (Boiling)

Figure 13 : Reactive rate (mol/kg/s) : CFM, k - ε, Gas – Liquid (~1:1)

In supercritical condition the surface tension drastically decrease. To observe the influence of σ, with have made calculation with an arbitrary value for σ witch is 10^{-6} N / m. The flame length decrease with the surface tension (Figure 14).



$\sigma = 1.32\ 10^{-2}$ N / m



$\sigma = 1\ 10^{-6}$ N / m

Figure 14 : Reactive rate (mol/kg/s) : Liquid, q - ω, oxygen (injection except σ)

3.5. Global case result

This case correspond to the following condition:

- Liquid injection for oxygen
- Turbulence model: q - ω
- Combustion model: CFM
- Surface tension $\sigma = 1\ 10^{-6}$ N/m
- Oxygen thermodynamics properties take at 85 K (injection)

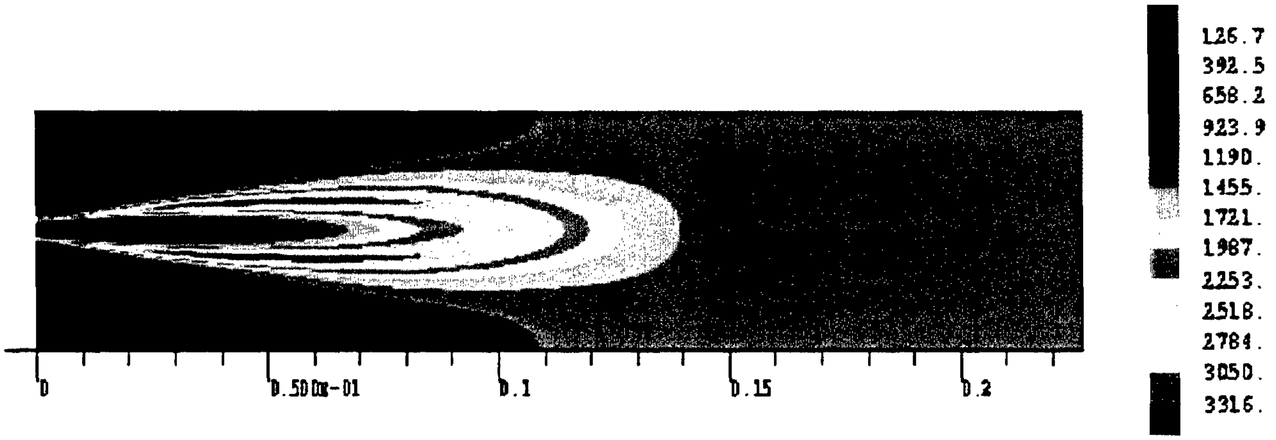


Figure 15 : Temperature (K)

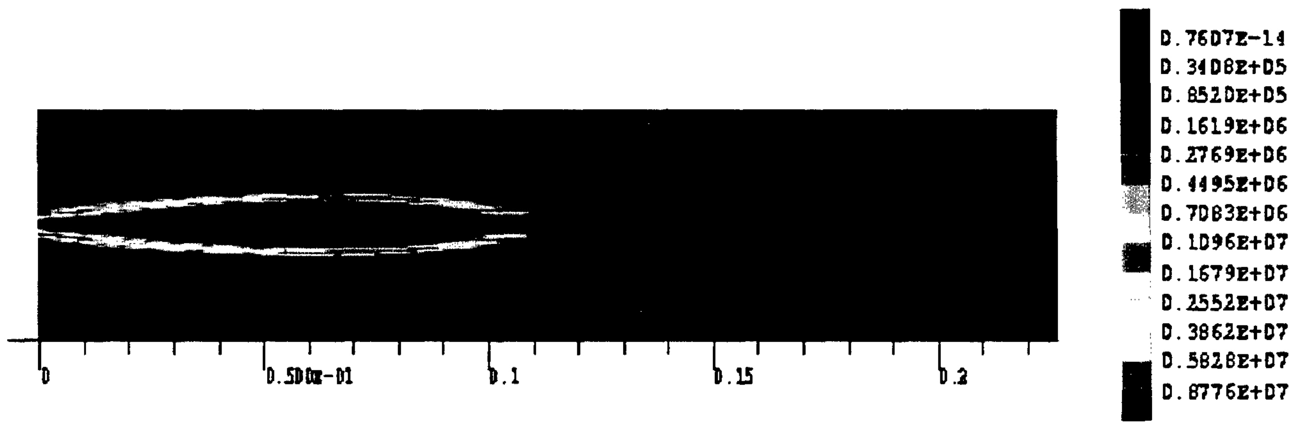


Figure 16 : Reactive rate (mol/kg/s)

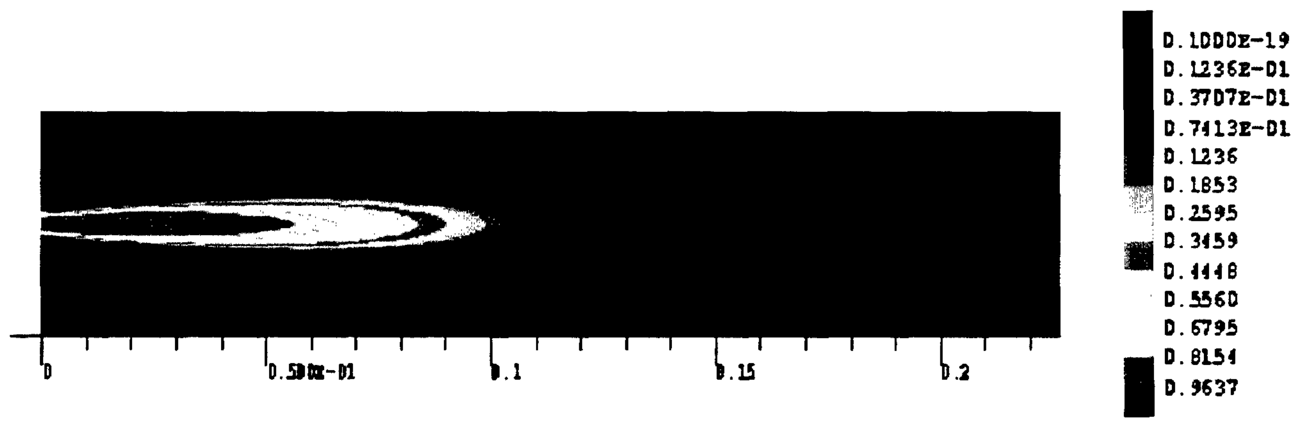


Figure 17 : O_2 mass fraction

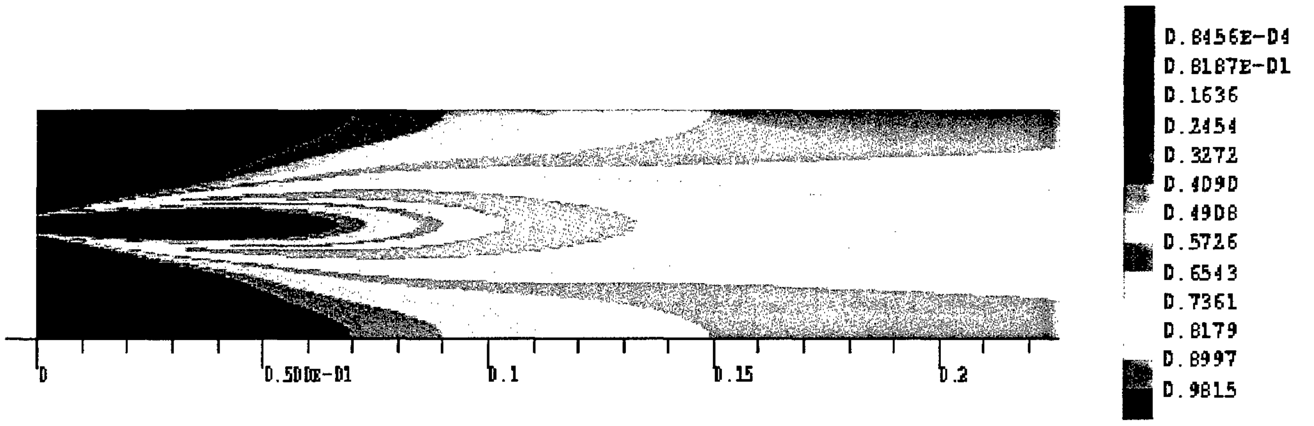
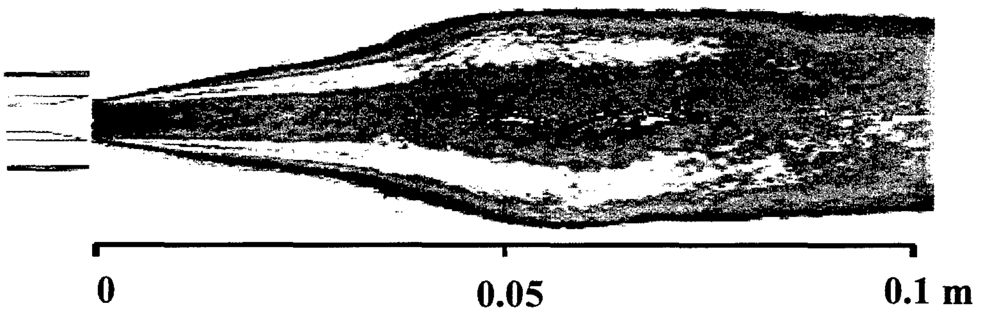


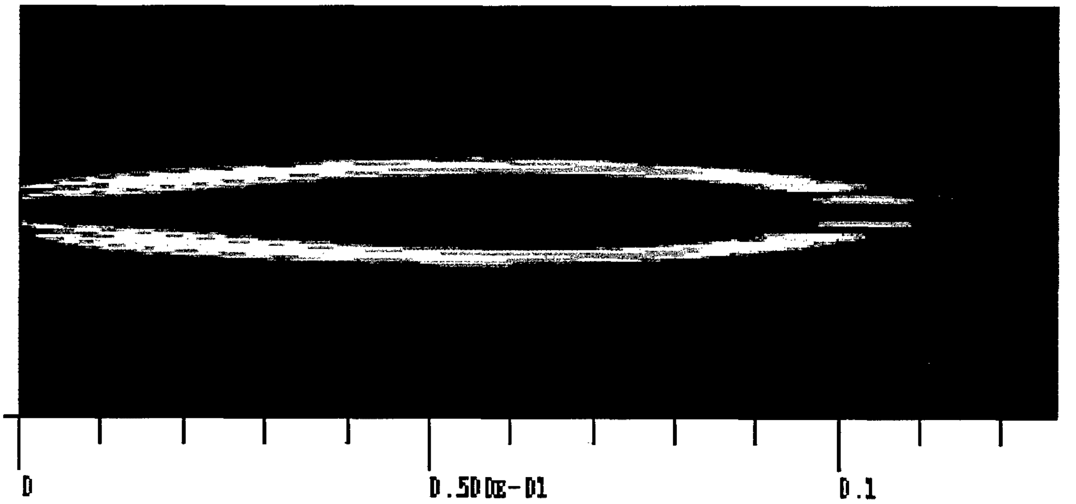
Figure 18 : H_2O mass fraction

3.6. Comparison with experimental results

If we compare the axisymetrical OH* emission image obtained experimentally with the most comparable calculated variable (the reactive rate), we obtain Figure 19. We observe a good agreement in the near field of the injector, but the second part of expansion of the flame is not obtained with calculation.



Axisymetrical average OH* emission image



Calculated reactive rate

Figure 19 : Comparison experiment – calculation

Experimentally [2] observe an expansion angle of 3.4° for OH* emission and 5.1° for H_2O emission. If we measure the reactive rate angle obtained by calculation, we have 4.0° (Figure 20). This value is coherent with experimental result.

Figure 20 : Calculated reactive rate expansion angle

4. CONCLUSION

The calculations performed for this test case RCM-3 show important difference on obtained results. Nevertheless, they are in good agreement with experimental results even if they are few for this operating point (A-60).

The lagrangian approach for oxygen generates some interrogation when it's used in supercritical condition. It appears that a real gas law for oxygen should be interesting for eliminates all the problems relative to droplet injection.

RÉFÉRENCES

[1] Test cas RCM-3, Mascotte single injector – 60 bar-, Test case specification for the 2^{nd} *International Workshop on Rocket Combustion Modeling.*

[2] Tripathi A., Structure de flammes cryotechniques à haute pression, *Thèse École Centrale Paris,* (2001)